

# A note on possible interpretations for the $D_{S^*J}^+(2632)$ observed by SELEX

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## Abstract

We suggest some possible interpretations for the  $D_{S^*J}^+(2632)$  observed by SELEX. The  $D_{S^*J}^+(2632)$  could be the first radial excitation of the  $1^-$  ground state  $D_s^*(2112)$ , and its unusual decay patten might be hopefully explained by the node structure of the wave functions. In addition, the  $D_{S^*J}^+(2632)$  could also be a  $c\bar{s}g$  hybrid state or a  $(cs)_3^* - (\bar{s}\bar{s})_3$  (diquark-antidiquark) bound state.

Very recently the SELEX Collaboration has reported the first observation of a charm-strange meson  $D_{S^*J}^+(2632)$  in the charm hadro-production experiment E781 at Fermilab[1]. The  $D_{S^*J}^+(2632)$  is observed in the  $D_s^+\eta$  decay channel with a significance of  $7.2\sigma$  and in the  $D^0K^+$  decay channel with a significance of  $5.3\sigma$ . The mass and width of this state are found to be  $M = 2632.6 \pm 1.6MeV$  and  $\Gamma < 17MeV$  (at 90% confidence level). This narrow state has a rather unusual decay patten that it is dominated by the  $D_s^+\eta$  decay mode with a very small ratio  $R = \Gamma(D^0K^+)/\Gamma(D_s^+\eta) = 0.16 \pm 0.06$ .

For the  $c\bar{s}$  mesons, aside from the ground state doublet [ $D_s(1969)$ ,  $D_s^*(2112)$ ] of  $[0^-, 1^-]$  states, as well as the  $D_{s1}(2536)$ ,  $D_{sJ}(2573)$ , which probably correspond to the  $J^P = 1^+, 2^+$  states being the P-wave excitations with the light quark angular momentum  $j = 3/2$ , in 2003 the BaBar collaboration reported the first observation of a massive, narrow charm-strange meson  $D_{s0}(2317)$  below the DK threshold [2]. CLEO [3] and BELLE [4] subsequently confirmed the existence of  $D_{sJ}(2317)$ , and further found another narrow higher-lying state  $D_{sJ}(2460)$ . The finding of [ $D_{sJ}(2317)$ ,  $D_{sJ}(2460)$ ] has stimulated many theoretical explanations for these two states[5]. Most likely, they may correspond to the  $J^P = 0^+, 1^+$  states being the P-wave excitations with the light quark angular momentum  $j = 1/2$ . In particular, in the chiral models for the heavy-light mesons, parity doublers are predicted to have the same mass splittings, and the ground state doublet [ $D_s(1969)$ ,  $D_s^*(2112)$ ] of  $[0^-, 1^-]$  states would have a parity-partner  $[0^+, 1^+]$  pair, which are very likely to be the observed [ $D_{sJ}(2317)$ ,  $D_{sJ}(2460)$ ][6, 7]. In 2004, the new state  $D_{S^*J}^+(2632)$  observed by SELEX with unusual decay modes will certainly be interesting in finding its own place in the heavy-light systems.

In the following we will present some discussions on the possible interpretations for the  $D_{S^*J}^+(2632)$  state.

- (1). The  $D_{S^*J}^+(2632)$  could be the first radial excitation of the  $1^-$  ground state  $D_s^*(2112)$ .

The  $D_{S_J}^+(2632)$  can decay into two pseudoscalar mesons  $D_s^+\eta$  or  $D^0K^+$ , so it should have  $J^P = 0^+, 1^-, 2^+, \dots$ . For the vector meson, the mass difference between the ground state and its first radial excitation ranges between 550-650 MeV. This can be seen from the observed  $2S$  and  $1S$  mesons. For instance, the  $2S$  and  $1S$  states are found to be, e.g.,  $\omega(1420)$  and  $\omega(782)$  for the light-light mesons;  $\psi(3686)$  and  $J/\psi(3097)$  for charmonium; and  $\Upsilon(10023)$  and  $\Upsilon(9460)$  for bottomonium. The mass difference between  $D_{S_J}^+(2632)$  and  $D_s^*(2112)$  is 520 MeV, it is marginal but still acceptable for the excitation energy of the  $2S$  heavy-light vector mesons, considering the fact that the P-wave excitation energy of  $D_{s,J}(2317)$  is considerably smaller than that for the observed light-light and heavy-heavy mesons and the conventional potential model calculations.

As the radial excitation of the  $1^-$  ground state  $D_s^*(2112)$ , the  $D_{S_J}^+(2632)$  could have a small decay width and unusual decay modes due to the node structure in its wave function. For the OZI allowed hadronic decay, the decay amplitude is related to the overlap integral of the wave functions of the initial and final state hadrons, and therefore is sensitive to the node structure of the wave functions: the sign-changing wave function of the radially excited states may result in substantial suppression for the decay rates of certain modes. The unusual experimental result in charmonium spectrum that the  $\psi(4030)(= \psi(3S))$  has a dominant decay amplitude to the  $D^*\bar{D}^*$  mode (with a very small  $Q$ -value) over the  $D\bar{D}$  mode (with a much larger  $Q$ -value) might be explained by the observation[8] that the nodes of the wave function and the different  $Q$ -value in each of these decays allow to understand the failure of the simple phase space argument. Indeed, the nodes of the wave functions lead to existence of zeros of the decay amplitude in the momentum of the decay products, which are responsible for the suppression of certain decay modes. The widths of the  $\psi(4414)(= \psi(4S))$  decaying into all ground state charmed meson pairs were estimated to be only about 15 MeV, despite of the very large phase space[8]. Although in [8] the quark pair creation model (i.e. the  $^3P_0$  model) was used we expect the qualitative features obtained there should hold regardless which specific model for describing the quark pair creation was used (see also[9] for the treatment in the Cornell model).

If the above features also hold for the decays of the radially excited heavy-light mesons, it would be not impossible to understand why the  $D_{S_J}^+(2632)$  could have a narrow width (say, of order 10 MeV) and could even have the decay mode  $D_s^+\eta$  (with a smaller  $Q$ -value and a  $s\bar{s}$  quark pair creation) dominating over the decay mode  $D^0K^+$  (with a larger  $Q$ -value and a  $u\bar{u}$  quark pair creation). Here in the former case the recombined  $s\bar{s}$  in the final state can be projected on the  $\eta$  meson according to the following relations (see,e.g.[10])

$$\begin{aligned} s\bar{s} &= 1/\sqrt{3}(\cos\theta - \sqrt{2}\sin\theta)\eta' - 1/\sqrt{3}(\sqrt{2}\cos\theta + \sin\theta)\eta \\ &= 0.72(0.82)\eta' - 0.69(0.57)\eta, \end{aligned} \quad (1)$$

$$\begin{aligned} 1/\sqrt{2}(u\bar{u} + d\bar{d}) &= 1/\sqrt{3}(\cos\theta - \sqrt{2}\sin\theta)\eta + 1/\sqrt{3}(\sqrt{2}\cos\theta + \sin\theta)\eta' \\ &= 0.72(0.82)\eta + 0.69(0.57)\eta', \end{aligned} \quad (2)$$

where  $\theta$  is the  $\eta - \eta'$  mixing angle, and the numerical values of the projection coefficients are obtained for  $\theta = -11^\circ(-20^\circ)$ . From eq.(1) and the observed ratio  $R = \Gamma(D^0K^+)/\Gamma(D_s^+\eta) = 0.16 \pm 0.06$  we see that the required suppression factor for the  $D^0K^+$  decay mode would be in fact larger than a factor of 13, indicating the demand that the momentum in the  $D^0K^+$  mode is very close to the zero of the decay amplitude. As already noted that in general the zeros in the decay amplitude are very sensitive to the wave functions and interquark potentials in use [11]. So, obviously a quantitative understanding for the  $D_{S_J}^+(2632)$  (as the  $2S$  radial excitation) decay widths of various channels would need an elaborate model to perform the calculations and to see whether the required suppression can be realized. This will be left for the future consideration. (Note that the decay to the P-wave charmed meson e.g.  $D_1(2420)(J^P = 1^+)$

associated with the kaon would be favored for the  $D_{S_J}^+(2632)$  decay if it is the  $J^P = 1^-$  radial excitation, but it is kinematically forbidden.)

If the  $D_{S_J}^+(2632)$  is the first radial excitation of the  $1^-$  ground state  $D_s^*(2112)$ , it would also decay to  $D_s^*(2112)\pi\pi$  but only with a small branching ratio. The radiative decay to  $D_s(1969)\gamma$  should be totally negligible. The quantum number  $J^P = 1^-$  could be examined from the angular distributions of the decay products. Moreover, we should also see the first radial excitation of the  $0^-$  ground state  $D_s(1969)$  at about 2490 MeV, of which all the OZI allowed decays e.g.  $D^*K, DK^*, D^*K^*, \dots$  are kinematically forbidden, and it can only decay to  $D_s\pi\pi$  via soft gluon emission and hadronization to  $\pi\pi$ . Of course, if its mass is above the  $D^*K$  threshold it would have the OZI allowed decays. The first radial excitation of the  $D_s^*(2112)$  should be observable in the  $B$  meson decays at Belle and BaBar, and in the  $e^+e^-$  annihilation at BES and CLEO-c, and may also be seen from the  $e^+e^-$  continuum at  $\sqrt{s} = 10.6$  GeV at Belle and BaBar, where the charmed-nonstrange meson pair production processes  $e^+e^- \rightarrow D^{(*)}\bar{D}^{(*)}$  have already been observed by Belle[12], and it should not be too difficult to detect  $D_s^{(*)}$  mesons and their radial excitations with higher statistics in the near future.

We finally note that any orbitally excited states of the  $c\bar{s}$  mesons (without nodes in their wave functions) such as the D-wave  $l = 2, j = 3/2, 5/2$  light quark excitations with  $J^P = 1^-, 2^-, 2^-, 3^-$  for the  $c\bar{s}$  systems could hardly explain the unusual decay pattern that  $R = \Gamma(D^0K^+)/\Gamma(D_s^+\eta) = 0.16 \pm 0.06$ .

(2). The  $D_{S_J}^+(2632)$  could be a  $c\bar{s}g$  hybrid state.

In some constituent gluon model for the hybrid states (see e.g.[13, 10]) the decay may proceed via the gluon conversion into the color-octet quark pairs (assuming SU(3) symmetry)

$$g \rightarrow 1/\sqrt{3}(u\bar{u} + d\bar{d} + s\bar{s})_8, \quad (3)$$

and then the color-octet quark pairs become the neutralized color-singlet ones by the gluon exchange with the color-octet  $(c\bar{s})_8$  component. If the gluon exchange does not flip the quark spin (e.g. via the long-ranged color-electric force), the final state from the gluon conversion in the hybrid would become the  $\omega$  or  $\phi$  mesons. If the short-ranged magnetic color-spin force induced by one gluon exchange flips the quark spin, the final state from the gluon in the hybrid would become the  $\eta$  or  $\eta'$  mesons. The short-ranged magnetic color-spin force could make the hybrid narrow. Hence a  $c\bar{s}g$  hybrid could mainly decay to a  $D_s$  meson plus a  $\eta$  meson if its mass does not allow it decaying into  $\omega$  or  $\phi$  mesons in the final state. The  $c\bar{s}g$  hybrid state could also decay into  $DK$  mesons via the quark rearrangement from the  $(c\bar{s})_8(u\bar{u} + d\bar{d} + s\bar{s})_8$  configuration. It is not clear dynamically whether the quark rearrangement can compete with the gluon exchange. If not, then the  $D_s\eta$  decay mode would dominate. However, this is still an open question in the constituent gluon model for the hybrid states because of the complication of the nonperturbative dynamics.

A study for the heavy-light hybrid  $Q\bar{q}g$  in the QCD sum rule approach may further shed light on the masses and decay widths of the  $Q\bar{q}g$  states[14]. It shows that in the heavy quark limit the lowest lying  $Q\bar{s}g$  state is the  $J^P = 1^-$  state with the strange quark and gluon excitation energy of about 1.7 GeV, and the  $J^P = 1^+, 0^+, 0^-$  hybrids will have higher masses. The total decay width of the  $1^-$   $Q\bar{q}g$  state would be about 300 MeV, but more than 80% are due to decays into the P-wave charmed meson associated with a light pseudoscalar meson (i.e. the partial decay width to the ground state charmed mesons is only about 10 MeV). If the observed  $D_{S_J}^+(2632)$  is the  $1^-$   $c\bar{s}g$  state (the mass estimate in the heavy quark limit for the charmed hybrid might suffer from large  $1/m_c$  corrections), it would then have a narrow width of the order 10 MeV, since decays involving the P-wave charmed mesons would not be kinematically allowed. This

would seem to be encouraging. But the mass of this  $c\bar{s}g$  hybrid state is estimated to be higher than 3.0 GeV, and it is hard to lower its mass down to 2.63 GeV by  $1/m_c$  corrections. Therefore it is not very likely to have this hybrid state as the candidate of  $D_{S_J}^+(2632)$ .

(3). The  $D_{S_J}^+(2632)$  could be a charmed baryonium (diquark-antidiquark)  $(cs)_{3^*} - (\bar{s}\bar{s})_3$  state.

In the recent studies for the pentaquarks, the diquark correlation has been emphasized [15]. If the diquark correlation does exist even in the S-wave hadrons, the diquark-antidiquark bound state or resonance (it was sometimes called the baryonium since it would easily decay to a baryon and antibaryon pair via a light quark pair creation if it has enough phase space) should also exist. As examples the  $(cq)_{3^*} - (\bar{c}\bar{q})_3$  (see, e.g.[16]) and  $(sq)_{3^*} - (\bar{s}\bar{q})_3$  (see, e.g. [10]) states have been discussed along with lots of studies by other authors. Here we would like to suggest the  $(cs)_{3^*} - (\bar{s}\bar{s})_3$  state be a possible candidate for the observed  $D_{S_J}^+(2632)$  state (see also [17, 18] for discussions on the four quark states). As in [15], assuming the diquark correlation exists even in the S-wave hadrons (this is different from the scenario of diquark clusters which are separated by large angular momentum barriers), then the  $(cs)_{3^*} - (\bar{s}\bar{s})_3$  state can only decay via the quark rearrangement into the  $c\bar{s}$  and  $s\bar{s}$  ( $D_s\eta$ ) mesons and then may have a narrow width. The  $s\bar{s}$  can further mix with  $u\bar{u} + d\bar{d}$  and this small mixing (not far from the ideal mixing) would lead to a small decay branching ratio to the  $DK$  mesons. Here the key assumption is that the  $(cs)_{3^*} - (\bar{s}\bar{s})_3$  has very small overlap with the  $(c\bar{s})_1 - (s\bar{s})_1$  color-configuration due to the diquark correlation, so that the  $(cs)_{3^*} - (\bar{s}\bar{s})_3$  can not simply fall apart into the  $D_s\eta$  mesons with a broad width (even for the S-wave state). If this is a right picture, we would have a nice interpretation for the  $D_{S_J}^+(2632)$ . But we have to know the dynamics for the diquark correlation. This is certainly a very interesting subject in low energy QCD. Here the  $\bar{s}\bar{s}$  diquark must have spin one since both flavor and spin are symmetric under the exchange of two quarks. Therefore the lowest  $(cs)_{3^*} - (\bar{s}\bar{s})_3$  state could have  $J^P = 1^+$ .

In summary, we have suggested some possible interpretations for the  $D_{S_J}^+(2632)$  observed by SELEX. The  $D_{S_J}^+(2632)$  could be the first radial excitation of the  $1^-$  ground state  $D_s^*(2112)$ , and its unusual decay pattern might be hopefully explained by the node structure of the wave functions. In addition, the  $D_{S_J}^+(2632)$  could also be a  $c\bar{s}g$  hybrid state or a  $(cs)_{3^*} - (\bar{s}\bar{s})_3$  (diquark-antidiquark) state, but these two assignments are less likely than the first one.

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*Note added.* After this work appeared in arXiv:hep-ph/0407091, Barnes et al.[19] and van Beveren et al.[20] independently reached the same conclusion that the  $D_{S_J}^+(2632)$  could be the first radial excitation of the  $1^-$  ground state  $D_s^*(2112)$ .

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